249

MASS TRANSFER FROM A VERY DILUTE GAS PHASE

465

by

RICHARD J. LIVINGSTON

B. S., Kansas State University, 1959

A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Chemical Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1965

Approved by:

Major Professor

LD
2668
T4
1965
L78
c.2
Document

TABLE OF CONTENTS

INTRODUCTION 1

LITERATURE SURVEY. 3

DIMENSIONAL ANALYSIS 4

TOWER EXPERIMENTATION. 6

EXPERIMENTAL PROCEDURE 10

DATA PROCESSING. 14

RESULTS AND CONCLUSIONS. 17

RECOMMENDATIONS. 21

ACKNOWLEDGMENTS. 22

TABLE OF NOMENCLATURE. 23

REFERENCES 26

APPENDICES

A. DIMENSIONAL ANALYSIS. 27

B. PHYSICAL PROPERTIES 32

C. SAMPLE CALCULATIONS 45

D. COMPOSITION PROFILE 51

E. RAW DATA. 53

INTRODUCTION

Mass transfer is basic to many of the processes in chemical engineering. The unit operations of distillation, absorption, and crystallization, for example, are basically mass transfer operations. It is imperative, for a continuing growth in chemical engineering practice, that there be advances in the development and understanding of the basic concepts and in the overall knowledge of mass transfer.

Most of the experimental work directed toward the understanding of the basic mechanisms in mass transfer have been carried out on apparatus having simple geometry. Systems frequently studied include a single sphere, a bed of spheres, and a flat plate (1). Plates are usually positioned in a vertical or a horizontal plane. This study dealt with a vertical flat plate.

The problem of the recovery of a component contained in a low concentration within a gas stream has received relatively little attention. This problem has received serious consideration on an industrial basis only when the recovered component is of high economic value or has toxic or obnoxious properties (2). A very low quality gas stream was studied in this work.

In general, the amount of an absorbate transferred from one phase to another is controlled by the equilibrium properties of the system, by the concentration driving force (i.e. the difference in concentration between the gas phase and the liquid phase with allowance for the equilibrium existing at the interface), and by the transfer or contact time. In most industrial cases, the composition of the gas stream fed to the absorber is fixed. In this case, the total quantity of material transferred, per unit quantity of absorbent, may be increased by increasing the change in composition of

the absorbent. The change in composition of the absorbent may be increased by increasing the time during which the absorbent is in contact with the gas.

The objective of this study was to determine a method of designing an absorption tower capable of handling a large quantity of low quality gas and specifically to determine a method of calculating the transfer area required under these conditions. In order to achieve this objective, it was necessary to investigate three areas:

1. A mathematical model:

   This includes the theoretical considerations of heat and mass transfer and of the characteristics of flow of fluid over the tower.

2. Materials:

   Selection of suitable tower materials and consideration of tower layout so that desirable control of holdup of absorption liquid and of turbulence within the body of the absorption liquid layer as well as optimum gas movement past absorption surfaces are obtained.

3. Scale-up:

   Establishment of appropriate parameters and the relationship between these parameters such that the results from small scale equipment may be used to predict the behavior of scaled-up equipment.

The selection of materials encompasses the selection of the absorbing liquid and the absorbed gas as well as the selection of tower materials which are suitable for use in an absorption tower. Water vapor in the air was chosen as the gas for the obvious reasons of abundance and economy. Glycols were chosen for the absorbing liquids because of their ease of handling, their relatively low toxicity, and their wide range of physical properties.

LITERATURE SURVEY

An initial literature survey was conducted in an effort to obtain information on free-convective, simultaneous heat and mass transfer. Simultaneous heat and mass transfer was expected because of the heats of condensation and solution involved in the transfer of mass from the vapor to the liquid phase. The free-convective condition was chosen for reasons of simplicity and economy. The use of forced convection would increase the expense of equipment beyond the economic limits because of the cost of the blower required.

Only two papers relating to free-convective heat and mass transfer were found in the literature.

Somers (3) and Mathers, Madden, and Piret (4), starting with the same physical model but using a slightly different approach, formulated basically the same equation. However, Mathers, Madden, and Piret carried the analysis farther and evaluated the constant present in the equation. The equation they derived is:

(Table of nomenclature on page 23)

$$Nu = 0.670 \left\{ Pr \left[Gr + (Pr/Sc)^{\frac{1}{2}} Gr' \right] \right\}^{\frac{1}{4}} \qquad (1)$$

The dimensionless groups of Equation (1) are the conventional ones except Gr' which is a mass transfer analogy of the Grashof number.

This model suggests a theoretical relationship between heat and mass transfer. The equation is valid for $0.9 < T_s/T_o < 1.0$ and $0.7 < Pr < 1.0$.

DIMENSIONAL ANALYSIS

A dimensional analysis was made to determine which dimensionless groups would be involved in an equation describing the mass transfer relation. The result of this dimensional analysis, given in Appendix A, is the dimensionless equation:

$$N_A/G_M = A\,(Sc)^B\,(Z)^C\,(Ga)^D\,(Re_G)^E\,(Re_A)^F\,(a/\rho_A)^G\,(\rho_A/\rho_G)^H\,(\mu_A/\mu_G)^I \qquad (2)$$

Equation (2) expresses a relationship between mass transfer and flow properties of a liquid and vapor. Equation (1) is a relation between heat transfer and mass transfer. The two equations do not relate the same quantities and are not comparable.

The final form of the absorption model was simplified to exclude heat transfer. This simplification was possible because of the extremely small amount of absorbate transferred to the liquid phase. If the material transferred made up a substantial part of the absorbent solution, so that the heats of condensation and mixing significantly influenced the heat balance, this simplification would not be possible.

N_A/G_M is the ratio of the mass rate of absorption of the absorbate to the mass rate of flow of the absorbent.

The Schmidt number, Sc, is the ratio of momentum diffusivity to molecular diffusivity. It appears in most correlations involving mass transfer.

The Ohnesorge number, Z, is the ratio of viscous force to the square root of the product of inertial and surface tension forces. It commonly appears in problems involving the atomization of fluids. In this study, it is involved in the breakdown of liquid streams and is therefore associated with the problem of channeling.

The Galileo number, Ga, is the ratio of the product of inertial force and gravitational force to the square of the viscous force. In general, it is related to the circulation of viscous fluids. In this study, it is probably concerned with internal crossflow in the absorbent, i.e. flow perpendicular to the mass transfer surface. As such, it tends to influence the concentration gradient of the absorbate in the liquid phase. The effective gravitational force has a direct influence on the Galileo number and is, therefore, a very important factor in the group. A value of 32.2 feet per second per second for gravitational acceleration was used in this study.

The ratio of absorptivity to absorbent density is a parameter expressing holdup. Absorptivity, a, represents the amount of liquid per unit volume of carrier tower material. The ratio, a/ρ_A, is, therefore, the volume of liquid per unit volume of carrier.

Because of the nature of the equation resulting from a dimensional analysis, a constant error in the value of some factor used will not affect the value of the exponent on the group involved. For example, if 64.4 feet per second per second had been used for gravitational acceleration in the Galileo number, so that the gravitational force calculated would have been twice the true value, D, the exponent on the Galileo number in Equation (2), would not have been affected. This can be shown simply. In the relation, $y = ax^b$, if the value $x' = kx$ is used instead of x, then the resulting equation will be $y = a'x'^b$. But $x' = kx$. Therefore, $y = a'k^b x^b$. The exponent on x is unaffected while the regression constant is in error by a factor of k^b. This fortunate circumstance, which allows the effect of a group to be determined in spite of a constant error in the calculation of the value of the group, is one factor which makes dimensional analysis such a powerful tool.

TOWER EXPERIMENTATION

In this study, absorbate was to be removed from a very large volume of low quality gas. It was realized that the energy requirements for moving large quantities of gas through reasonably sized columns of conventional design, such as perforated plate columns or packed towers, would be high. Also, column diameter, of a size sufficient to effect desirable total mass transfer, would be extremely large.

In order to circumvent these design problems, it was decided to design a tower such that the gas:liquid interface would be in the main body of the gas phase and natural currents (wind) would serve to move the gas over the absorbing surface. This would eliminate all costs of moving the gas phase and would permit simple tower construction.

It was anticipated that the overall mass transfer coefficient would be relatively low, therefore, it was decided to design the tower so that the interfacial surface per volume of liquid absorbent and the time of contact between gas and absorbent per unit volume of absorbent would be high.

These requirements suggested that the liquid absorbent should be spread into a thin layer. It was reasoned that a screen would provide a support for such a liquid surface.

Contact time per unit volume of liquid could be varied by varying the mass of absorbent per unit of interfacial area. This variable may be recognized as holdup. Holdup may be changed by changing the effective gravity, i.e. by changing the slope of the absorbent liquid support, or it may be varied by changing the depth of the liquid on an absorption surface having a constant slope.

A second possible type of liquid support was cloth which was itself supported by a stiff material of some kind. The same arguments concerning contact time and holdup that apply to the screen support also apply to the cloth support.

The absorption tower was designed in two parts, a feeding system and a liquid support. The feeding system was required to transport the liquid absorbent from storage at a constant flow rate and distribute it evenly over the top of the support tower. The flow rate control consisted of an overhead tank in which the liquid head was held approximately constant. A siphon inserted in a floating block of styrofoam with a drawn glass tip at the outlet completed the constant flow portion of the feeding section.

The initial distributor was required to distribute the absorbent evenly over the top of the liquid support so as to eliminate channeling as much as possible. The first distributor used consisted of a V-shaped trough covered with cloth into which the absorbent flowed. In the second distributor, the trough was filled with cellulose sponge. It was expected that the cellulose sponge would absorb the liquid and distribute it evenly over the top of the support. This model distributed the liquid more evenly than the first type had, but still did not provide as even distribution as was desired. Therefore, a third model, consisting of a short section of packed column, was designed. A box of Lucite which fit over the top of the liquid support was made. The box was filled with approximately nine inches of crushed porcelain. The absorbent flowed from the overhead storage and constant head tank, through the siphon, to the bed of crushed porcelain, where it was evenly distributed by the time it reached the liquid support.

The liquid support was designed to serve as a carrier and support for the liquid film of absorbent which is required if there is to be any mass transfer taking place. In order to achieve a desirable rate of mass transfer, it is necessary that the absorbent be spread evenly over the surface of the liquid carrier. Thus, it is necessary to minimize channeling as far as possible.

Channeling is the tendency for a flowing liquid to form streams covering only a portion of the surface available for flow but containing a large fraction of the liquid. The remainder of the surface available for flow may hold a very thin film of liquid or may be completely dry. Channeling is undesirable in a mass transfer operation since it reduces the effective area available for mass transfer.

In order to eliminate channeling as much as possible, redistributors are commonly used within a tower to redistribute the flowing liquid evenly over the entire tower. A redistributor may be of the same design as the initial distributor or it may be completely different in design. The only necessary criterion is that the liquid become evenly distributed over the tower once again.

The first support material which was used was a common household metal window screen made up of square meshes. The screen was mounted in a vertical plane. The screen was supported between two wooden frames which were clamped tightly together to minimize the possibility of the screen's shifting.

Liquid flowing over the tower channeled badly whether the wires were mounted in a vertical and horizontal position or diagonally to the horizon. The channeling was severe enough that it was easily detectable by the eye in normal runs. Redistributors were added to the tower in attempts to reduce

the amount of channeling. The first attempt at redistribution involved the use of crimps in the screening. The screening was crimped and bent up to form shallow cups running the width of the tower. This method was unsuccessful since the channeling was nearly unaffected by the redistributors. The remaining redistributors tried were various forms of cellulose sponge. The first attempt with the cellulose sponge was to attach horizontal strips of the sponge to the tower. This improved the liquid distribution considerably but channeling was still apparent. Staggered redistributors were tried with no more success than with the full horizontal redistributor. A third type, a redistributor in the shape of an inverted V, was also used. This model gave the best liquid redistribution of all the redistributors used to that time, but channeling was still easily perceived by eye.

At this point, it was decided that the single screen would not provide the desired even distribution of liquids. Therefore, a double screen, consisting of two single screens placed as closely together as possible without forcibly pressing, was tried. Two models of the double screen were used. In one, the wires of the two screens were parallel to one another, while in the other, the wires were diagonal. The double screen model channeled very badly. Even when inverted V-shaped redistributors were placed between the screens, the channeling was much worse than in the single screen tower.

Two other types of screening were used, with little success. A small mesh screen, automobile carburetor filter screen, was used in hopes that the closer weave would improve distribution. The closer weave proved to have the opposite effect. The other type of screen tried was an aluminum shade screen. This screen is formed from a flat sheet of aluminum which has had short slits cut into it. The part of the sheet immediately below

the slit is pressed down to form a cuplike opening. There are several columns of these openings on one screen. It was hoped that if the shade screen were attached as tightly as possible to a flat surface, the openings would act as small dams and serve to redistribute the flowing liquid over the surface. The shade screen was attached to a piece of pine lumber. A stream of liquid was introduced at the top of the column in a well distributed manner. An extremely large amount of channeling was apparent on the screen between the columns of openings.

The next trial was made on an apparatus which consisted of a piece of cotton sheeting stretched over a 1-in. by 1-in. pine board about three feet long. This system showed quite good flow characteristics. However, a dye tracer showed that there was some initial channeling which decreased slightly as flow continued down the tower. It soon became apparent that a thicker cloth and one which could provide its own redistribution would result in improved operations. A length of corduroy was stretched over the board with the ribs in a horizontal position. After a short time the board became warped, allowing the cloth to loosen. This allowed gross channeling in the open space in the center of the board. In order to avoid further problems with warpage, narrower, thinner boards with a large capacity for absorption were utilized. The final liquid film support consisted of a $\frac{1}{2}$-in. by 6-in. by 36-in. balsa board with corduroy tightly stretched around it.

EXPERIMENTAL PROCEDURE

Three towers were set up to take experimental data. In the final setup, the towers were arranged so that a fan placed at one end of the row of three

PLATE I

Absorption tower with components.

1. Distributor.
2. Liquid film support.
3. Wooden backing.

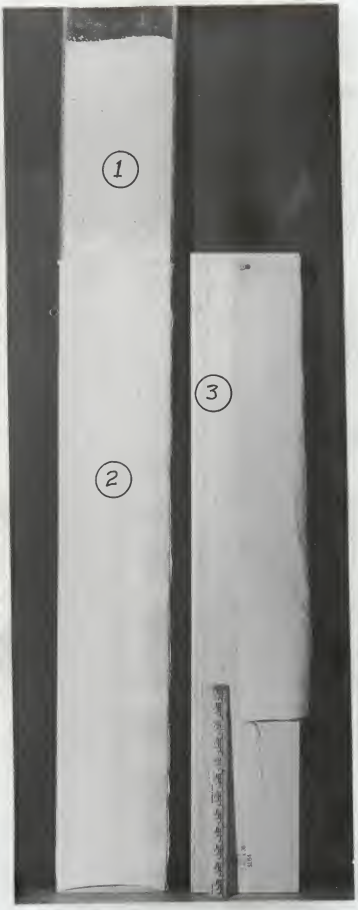


PLATE I

towers could move air past each one parallel to the face of the tower. Each tower was supplied with absorbent fluid from a different head tank. With this arrangement, three runs with different absorbent fluids could be made at the same time.

The experimental procedure was as follows. The tanks containing the absorbent were filled and the siphon started. After the liquid flow over the column had reached steady state conditions, approximately six hours, samples to be analyzed for water content were taken. It was determined that steady state conditions were reached by observation and by checking the change of water concentration with time at a specific point on the tower.

Seven samples were taken from the tower each time it was sampled. One sample was taken from the top of the tower, one from the bottom, and the remaining five from points spaced at six inch vertical intervals along the column. All samples were taken from points lying on the centerline of the tower in order to avoid edge effects as much as possible. The samples were taken with an eye dropper and were held in the dropper until they were analyzed for water concentration. Composition was determined by refractive index. The droppers were held in tightly capped bottles until analysis in order to eliminate the absorption of additional water from the atmosphere.

Five readings of refractive index were made for each sample. These five readings were averaged to yield the average refractive index which was used to determine the concentration of water in the sample. The standard deviation of the sets of samples was 3×10^{-9}.

The thickness of the liquid film on the tower was measured with a modified precision micrometer. The modified micrometer had a tripod base between the legs of which a needle point was lowered to measure the height

of the film surface. The needle point was brazed directly to the measuring face of the micrometer.

Atmospheric temperature and pressure were recorded and atmospheric humidity was determined with a sling psychrometer.

DATA PROCESSING

All data reduction was performed on an IBM 7094 computer. Equations for the required physical properties such as glycol density, viscosity, etc., were obtained by curve fitting and specific values were calculated as required. All curve fits were made by a standard linear regression program. The models to which the physical properties were fit and comparisons between values calculated from the regression equations and the values reported by Dow Chemical Co. (5), from which the curve fits were made, are given in Appendix B.

The dimensionless groups were calculated by a computer routine written for that purpose. A sample calculation and the computer flow sheet for these calculations are given in Appendix C. The dimensionless groups were curve fitted by the same linear regression routine as were the physical property correlations. The model to which the groups were fit is:

$$N_A/G_M = A(Sc)^B\ (Z)^C\ (Ga)^D\ (Re_G)^E\ (Re_A)^F\ (a/\rho_A)^G\ (\rho_A/\rho_G)^H\ (\mu_A/\mu_G)^I$$

The results of this analysis are given in the next section.

PLATE II

Modified micrometer showing method of use.

PLATE II

RESULTS AND CONCLUSIONS

Two sets of results were obtained, one for ethylene glycol and the other for propylene glycol. These are summarized in Table I. Equation (2), the normal form of the model to which the mass transfer data were fit, with the exponents for ethylene glycol is:

$$N_A/G_M = 1.729 \times 10^{-22} (Sc)^{8.981} (Z)^{0.0} (Ga)^{0.0} (Re_G)^{-0.01339} (Re_A)^{-0.8191} (a/\rho_A)^{1.329} (\rho_A/\rho_G)^{-4.704} (\mu_A/\mu_G)^{-1.557}$$

The same equation but with the exponents calculated for propylene glycol is:

$$N_A/G_M = 8.764 \times 10^{-40} (Sc)^{-22.165} (Z)^{2.707} (Ga)^{0.0} (Re_G)^{-0.008595} (Re_A)^{-0.9281} (a/\rho_A)^{20.433} (\rho_A/\rho_G)^{-8.293} (\mu_A/\mu_G)^{0.0}$$

The two regression equations were then rerun, dropping the least significant term, until all remaining terms had t values showing significance at the 95% level. The equations resulting from this procedure, summarized in Table II, are:

$$N_A/G_M = 3.511 \times 10^{-10} (Re_A)^{-0.7254} (\mu_A/\mu_G)^{-1.940}$$ for ethylene glycol, and

$$N_A/G_M = 2.512 \times 10^{-16} (Sc)^{-21.773} (Z)^{2.561} (Re_A)^{-0.8714} (a/\rho_A)^{17.159}$$ for propylene glycol.

R^2 is the coefficient of determination which is a numerical value for the fraction of variance in the dependent variable which can be explained in terms of the variance of the independent variables. The low R^2 of 37.1% for ethylene glycol and 28.4% for propylene glycol indicates that this model could be improved. That is, the model may not be complete; there may be other factors not being adequately considered.

The value of Student's "t" is an indication of the importance of the variable. For example, the Galileo number, Ga, appears to be of little importance as related to mass transfer by absorption over the range of conditions studied. However, it may be extremely important under other conditions. If the either the tower material or the liquid film had been thicker so that internal crossflow would have been stronger, the exponent on the Galileo number might have had a different value and a larger "t".

The facts that the exponents on the Schmidt number, Sc, the Ohnesorge number, Z, and the holdup parameter, a/ρ_A, are significant for propylene glycol and are not significant for ethylene glycol agree with the intuitive judgment that these parameters should be more significant for propylene glycol. Propylene glycol's higher viscosity and lower density would lead to the same conclusions independently. On the other hand, the appearance of the viscosity ratio as a significant term for ethylene glycol is somewhat surprising. Intuitively, it would seem that the viscosity term would play a more important part in the propylene glycol correlation than in the ethylene glycol correlation.

The Reynold's number of the absorbent appears to be of vital importance since it has a "t" of 6.464 and 4.514 for ethylene and propylene glycol respectively, compared with a $t_{0.05}$ of 1.99 for both sets of data. The status of the other exponents is more uncertain, ranging from extremely to only moderately unlikely that the exponent is significantly different from zero; and even then, the decision varies with the system as has been seen.

Table I. Values of coefficients, standard errors of estimate, and "t" values for all groups.

	Ethylene Glycol	Propylene Glycol
A, Regression coefficient	-50.118	-89.949
(Exponent on e)	0.849	1.054
SEE	59.032	85.341
"t"		
B, Exponent on Sc	8.981	-22.165
SEE	25.933	23.890
"t"	0.346	0.928
C, Exponent on Z	0.0	2.707
SEE	0.0	0.731
"t"	0.0	3.705
D, Exponent on Ga	0.0	0.0
SEE	0.0	0.0
"t"	0.0	0.0
E, Exponent on Re_G	-0.01339	-0.008595
SEE	0.009775	0.01507
"t"	1.370	0.5703
F, Exponent on Re_A	-0.8191	-0.9281
SEE	0.1389	0.2262
"t"	5.896	4.103
G, Exponent on a/ρ_A	1.329	20.433
SEE	6.509	7.548
"t"	0.2042	2.917
H, Exponent on ρ_A/ρ_G	-4.704	-8.293
SEE	25.971	28.429
"t"	0.1811	0.2917
I, Exponent on μ_A/μ_G	-1.557	0.0
SEE	0.8384	0.0
"t"	1.858	0.0
R^2, Coefficient of determination	0.392	0.288
$t_{0.05}$, Student's t at 95% level	1.99	1.99

Table II. Values of coefficients, standard errors of estimate, and "t" values for significant groups.

	Ethylene Glycol	Propylene Glycol
A, Regression coefficient	-21.774	-29.938
(Exponent on e)	0.8435	1.045
SEE	25.813	28.652
"t"		
B, Exponent on Sc	-	-21.773
SEE	-	10.283
"t"	-	2.117
C, Exponent on Z	-	2.661
SEE	-	0.6992
"t"	-	3.807
F, Exponent on Re_A	-0.7254	-0.8714
SEE	0.1122	0.1930
"t"	6.464	4.514
G, Exponent on a/ρ_A	-	17.159
SEE	-	4.632
"t"	-	3.704
I, Exponent on μ_A/μ_G	-1.940	-
SEE	0.5263	-
"t"	3.686	-
R^2, Coefficient of determination	0.371	0.284
$t_{0.05}$, Student's t at 95% level	1.99	1.99

RECOMMENDATIONS

In view of the low value of R^2 for the two correlations and the varying values of "t" for the exponents, it is recommended that further studies be conducted in order to obtain a clearer view of the relationship between the variables. In order to do this, it will probably be necessary to use a different relation as the model. A model based on the two film theory or some other theoretical basis might be sufficient. The Reynold's number of the glycol will, in all probability, be present and one or more of the other variables used in this correlation might be present.

Specific experiments to examine the effects of individual variables may be set up as desired. For example, to study the effect of the Galileo number, the tower may be tilted from the vertical so that the gravitational force in the plane of the tower can be varied. Other experiments can be devised for the other variables.

ACKNOWLEDGMENTS

The author wishes to express his sincere gratitude to Professor Raymond C. Hall for his guidance and invaluable suggestions which made this investigation possible.

The encouragement and backing of my wife, Lou Ann, which supported my sometimes faltering steps, is greatly appreciated.

The generosity of Phillips Petroleum Company and its computing department in allowing the use of the IBM 7094 computer eliminated many tedious hours of hand calculations.

The funds supporting this project were supplied by the Agricultural Experiment Station of Kansas State University.

TABLE OF NOMENCLATURE

a = absorptivity, ~~#~~ g./cu.cm.

A = coefficient in linear regression equation

A = area, ~~#~~ sq.cm.

B = coefficient in linear regression equation

c = concentration, ~~#~~ lb/cu.ft.

c_p = heat capacity, ~~#~~ B.T.U./lb.

C = coefficient in linear regression equation

D = coefficient in linear regression equation

D_V = diffusivity, ~~#~~ sq.ft./hr.

E = coefficient in linear regression equation

F = force, ~~#~~ lb.$_F$.

F = coefficient in linear regression equation

g = acceleration due to gravity, ~~#~~ ft./sec./sec.

g_c = Newton's law constant, ~~#~~ (ft.)(lb.) / (lb.force)(sec./sec.)

G = coefficient in linear regression equation

G_M = absorbent mass flow rate, ~~#~~ mols./(min.)(sq.cm.)

Ga = Galileo number, ~~#~~ $gL^3\rho^2/\mu^2$

Gr = Grashof number, ~~#~~ $(gL^3\rho^2\beta/\mu^2)(T_0-T_s)$

Gr' = modified Grashof number, ~~#~~ $(gL^3\rho^2\alpha/\mu^2)(c_0-c_s)$

h = heat transfer coefficient, ~~#~~ B.T.U./(sq.ft.)(hr.)($^\circ$R)

H = coefficient in linear regression equation

I = coefficient in linear regression equation

k = thermal conductivity, ~~#~~ B.T.U./(ft.)(hr.)($^\circ$R)

l = length of individual section of transfer tower, ~~#~~ in.

L = characteristic length, $\not{U}$ units of length

L_p = wetted perimeter, $\not{U}$ in.

M = molecular weight, $\not{U}$ g./g.mol.

$\mathcal{M}$ = water transferred, $\not{U}$ mol./min.

N_A = mass transfer rate, $\not{U}$ mol./(min.)(sq.cm.)

Nu = Nusselt number, $\not{U}$ hL/k

P_A = partial pressure of water in ambient air, $\not{U}$ mm. Hg

P_{eq} = vapor pressure of absorbent solution, $\not{U}$ mm. Hg

P = pressure, $\not{U}$ mm. Hg

Pr = Prandtl number, $\not{U}$ $c_p\mu/k$

Q = volumetric flow rate, $\not{U}$ cc./min.

Re = Reynold's number, $\not{U}$ $4W/L_p\mu$

S = molar flow rate, $\not{U}$ mol./min.

Sc = Schmidt number, $\not{U}$ $\mu/\rho D_v$

"t" = Student's t

t = thickness of absorbent film, $\not{U}$ in.

t_c = thickness of cloth carrier, $\not{U}$ in.

T = temperature, $\not{U}$ ^oF

u = air velocity, $\not{U}$ ft./min.

w = width of absorbing tower, $\not{U}$ in.

W = mass velocity, $\not{U}$ g./min.

x = weight fraction water in absorbing liquid

Z = Ohnesorge number, $\not{U}$ $\mu/\sqrt{\rho g_c L \sigma}$

$\not{U}$ = has units of

$\not{D}$ = has dimensions of

Greek Symbols

α = specific densification coefficient, ~~=~~ cu.ft./lb.

β = coefficient of compressibility, ~~=~~ $^{o}R^{-1}$

θ = time, ~~=~~ min.

λ = thermal conductivity, ~~=~~ cal./(min.)(cm.)(^{o}C)

μ = viscosity, ~~=~~ centipoise

ρ = density, ~~=~~ g./ml.

σ = surface tension, ~~=~~ dynes/cm.

Subscripts

a = average conditions over section of absorption tower

A = absorbent stream

f = conditions at bottom of section of absorption tower

G = gas stream

i = conditions at top of section of absorption tower

o = conditions at infinite distance from tower surface, in Appendix C, conditions at top of absorption tower

s = conditions at tower surface

REFERENCES

1. Treybal, Robert E., "Mass Transfer Operations", McGraw-Hill, New York, 1955.

2. Shreve, R. Norris, "The Chemical Process Industries", McGraw-Hill, New York, 1956.

3. Somers, E. V., Journal of Applied Mechanics, 23 #2, 295 (1956).

4. Mather, W. G., A. J. Madden, Jr., and Edgar L. Piret, Industrial and Engineering Chemistry, 49 #6, 961 (1957).

5. Dow Chemical Company, "Glycols, Properties and Uses", Midland, Michigan, 1961.

6. Snedecor, George W., "Statistical Methods", Iowa State College Press, Ames, Iowa, 1956.

7. Perry, J. H., Ed., "Chemical Engineer's Handbook", McGraw-Hill, New York, 1950.

8. Ipsen, D. C., "Units, Dimensions, and Dimensionless Numbers", McGraw-Hill, New York, 1960.

APPENDIX A

DIMENSIONAL ANALYSIS

There are fourteen variables which need be considered in the analysis of the system. These are:

N_A	Rate of mass transfer	~~D~~	$M/L^2\theta$
G_M	Absorbent mass flow rate	~~D~~	$M/L^2\theta$
W_G	Vapor mass velocity	~~D~~	M/θ
L	Characteristic length	~~D~~	L
D_v	Diffusivity	~~D~~	L^2/θ
μ_A	Absorbent viscosity	~~D~~	$M/L\theta$
ρ_A	Absorbent density	~~D~~	M/L^3
g_c	Newton's law constant	~~D~~	ML/θ^2F
g	Acceleration due to gravity	~~D~~	L/θ^2
σ_A	Absorbent surface tension	~~D~~	F/L
a	Absorptivity	~~D~~	M/L^3
μ_G	Vapor viscosity	~~D~~	$M/L\theta$
ρ_G	Vapor density	~~D~~	M/L^3
W_A	Absorbent mass velocity	~~D~~	M/θ

However, G_M can be expressed as W_A/A, where A is the area through which flow is measured. In terms of the above variables, this would be expressed as W_A/L^2. This, then, reduces the number of variables by one. The function to be analyzed is:

$$N_A = f(W_G, L, D_v, \mu_A, \rho_A, g_c, g, \sigma_A, a, \mu_G, \rho_G, W_A) \qquad (1\text{-}A)$$

which can be represented dimensionally as:

$$N_A \quad A\,(W_0)^a\,(L)^b\,(D_v)^c\,(\mu_A)^d\,(\rho_A)^e\,(g_c)^f\,(g)^g\,(\sigma_A)^h\,(a)^i$$

$$(\mu_0)^j\,(\rho_0)^k\,(W_A)^l \qquad (2\text{-}A)$$

The remainder of the dimensional analysis is carried out by the Bridgman method (7, 8). The dimensions are substituted for the variables. The exponents on the dimensions are then equated to give four equations which must be solved simultaneously to yield solutions which can be used to form dimensionless groups.

$$M/L^2\theta = (M/\theta)^a\,(L)^b\,(L^2/\theta)^c\,(M/L\theta)^d\,(M/L^3)^e\,(ML/\theta^2F)^f\,(L/\theta^2)^g$$
$$(F/L)^h\,(M/L^3)^i\,(M/L\theta)^j\,(M/L^3)^k\,(M/\theta)^l \qquad (3\text{-}A)$$

Equating exponents on each dimension:

$$\left.\begin{aligned} M:&\ 1 = a + d + e + f + i + j + k + l \\ L:&\ -2 = b + 2c + d - 3e + f + g - h - 2i - j - 3k \\ \theta:&\ -1 = -a - c - d - 2f - 2g - j - l \\ F:&\ 0 = -f + h \end{aligned}\right\} \qquad (4\text{-}A)$$

Equations (4-A) are solved simultaneously by a straightforward method. In this solution, four of the exponents are stated in terms of the remaining eight. The four exponents for which solutions were found are b, d, e, and f. The twelve exponents can be stated as:

$$
\begin{aligned}
a &= a \\
b &= -1 - a + 3g + h - 1 \\
c &= c \\
d &= 1 - a - c - 2g - 2h - j - 1 \\
e &= c + 2g + h - i - k \\
f &= h \\
g &= g \\
h &= h \\
i &= i \\
j &= j \\
k &= k \\
l &= l
\end{aligned}
\qquad (5\text{-}A)
$$

It should be explained that the above solution is only one possible solution. Other solutions, i.e. choosing to solve for different sets of four exponents, will give different dimensionless groups.

The Equations (5-A) are then substituted into Equation (2-A).

$$
N_A = A\,(W_G)^a\,(L)^{-1-a+3g+h-1}\,(D_v)^c\,(\mu_A)^{1-a-c-2g-2h-j-1}
$$
$$
(\rho_A)^{c+2g+h-i-k}\,(\varepsilon_c)^h\,(g)^g\,(\sigma_A)^h\,(a)^i\,(\mu_G)^j\,(\rho_G)^k\,(W_A)^l \qquad (6\text{-}A)
$$

When all variables with like powers are collected, the dimensionless equation is formed.

$$
N_A L/\mu_A = A\,(W_G/L\mu_A)^a\,(D_v\rho_A/\mu_A)^c\,(gL^3\rho^2_A/\mu^2_A)^g\,(\rho_A L\sigma_A\varepsilon_c/\mu^2_A)^h\,(a/\rho_A)^i
$$
$$
(\mu_G/\mu_A)^j\,(\rho_G/\rho_A)^k\,(W_A/L\mu_A)^l \qquad (7\text{-}A)
$$

When a dimensionless solution has been formed, it is necessary to inspect it to be certain that all the dimensionless groups are meaningful. In general, any desired dimensionless grouping can be formed by proper selection of exponents, but in practice, the selection of exponents is controlled by a desire to obtain as many dimensionless groups as possible which have recognized meaning. In spite of this restriction, some groups whose physical meaning is not clear are usually formed. Two groups in Equation (7-A) fall into this category. The dependent group, $N_A L/\mu_A$, although dimensionally correct, would be more meaningful if stated as N_A/G_M. The first group on the right side of the equation is the second questionable group. It has mixed units, that is, the mass velocity of the gas and the viscosity of the absorbent. The last group on the right side has the same form, but units of the absorbent on all variables. Therefore in the first term, the viscosity of the absorbent was changed to the viscosity of the absorbent was changed to the viscosity of the gas.

Five of the terms in Equation (7-A) are recognized as accepted dimensionless groups. These are Reynold's number of gas and of absorbent, Schmidt number, Galileo number, and Ohnesorge number. With the changes made above and conversion to accepted nomenclature, Equation (7-A) becomes:

$$N_A/G_M = A\,(Re_G)^a\,(Sc)^{-c}\,(Ga)^g\,(Z)^{-2h}\,(a/\rho_A)^i\,(\mu_G/\mu_A)^j$$

$$(\rho_G/\rho_A)^k\,(Re_A)^l \qquad (8\text{-}A)$$

A change can be made in a/ρ_A to put it in a form which is more easily worked with. The units on absorptivity, a, are mass of absorbent per unit volume of carrier. Since the area in the plane of the carrier is the same for both the carrier and the absorbent, then a/ρ_A is the same as the ratio

of the absorbent film thickness to the thickness of the carrier, t/t_c. One other change is made to make the equation easier to work with. If the viscosity and density ratios are inverted, the computer program coding is made slightly easier. The final form of the dimensionless equation is:

$$N_A/G_M = A\,(Re_G)^a\,(Sc)^b\,(Ga)^c\,(Z)^d\,(t/t_c)^e\,(\mu_A/\mu_G)^f\,(\rho_A/\rho_G)^g\,(Re_A)^h \qquad (9\text{-}A)$$

APPENDIX B

PHYSICAL PROPERTIES

The physical properties of the system; absorbent density, absorbent viscosity, surface tension, vapor pressure, and air viscosity, were correlated by models to which the data were fit by the least squares method. The models used were empirical but were chosen to give as good a fit as was possible. The models and coefficients for each of these physical properties will follow.

The value of the diffusivity of water vapor in the air at 32°F of 0.853 sq.ft./hr. was taken from Perry (7).

Absorbent Density

$$\rho_A = A + BT + CT^2 + Dx + ETx + FT^2x + Gx^2 + Hx^2 + IT^2x^2$$

	Ethylene glycol	Propylene glycol
A	1.138375	1.052936
B	-0.0003734119	-0.00007300824
C	-0.00000004586764	-0.000002319983
D	-0.6186682	0.1134615
E	0.0	-0.001554638
F	-0.0000005761387	0.00001022476
G	-0.1080837	-0.2039127
H	0.0008893013	0.002447069
I	-0.000003149034	-0.00001448998

Absorbent Viscosity

$$\ln \mu_A = A + BT + CT^2 + Dx + Ex + FT^2x + Gx^2 + Hx^2 + IT^2x^2$$

	Ethylene glycol	Propylene glycol
A	4.828053	7.004401
B	-0.03201962	-0.05275448
C	0.00006172340	0.0001379838
D	-3.201962	-6.031601
E	0.0	0.0
F	0.00006536767	0.0001344718
G	-1.769806	2.866028
H	0.03804016	0.0008449554
I	-0.0001945049	-0.0001546144

Surface Tension

$$\ln \sigma_A = A + Bx + Cx^2 + Dx^3 + Ex^4 + Fx^5$$

	Ethylene glycol	Propylene glycol
A	3.850768	3.590716
B	0.3061910	0.3115540
C	0.1461029	-0.3100586
D	-0.2784729	3.173828
E	0.0	-6.080078
F	0.2344513	3.850586

Vapor Pressure

$\ln p_A = A + B/(T\ 460) + C/x + D/x^2 + E/x^3$

	Ethylene glycol	Propylene glycol
A	21.41319	21.84841
B	-9893.922	-10119.93
C	-0.1335599	-0.1103056
D	0.002019504	0.001487864
E	-0.00001064019	-0.000007103517

Air Viscosity

$\ln \mu_G = A + Bq + Cq^2 + Dq^3 + Eq^4 + Fq^5 + Gq^6$

where $q = \ln(T\ 460)$

A	-10.81196
B	1.459709
C	0.0
D	-0.006287456
E	0.0
F	0.0
G	-0.000001342385

The following plates give a graphical comparison between the original data (5) and the curve fits. In all cases in which the property is a function of both the temperature and the composition, only one composition is shown. The composition shown was chosen at random from the compositions given in the back calculations in the curve fit routine. Representative values are shown for both ethylene and propylene glycol where necessary.

PLATE B-I

Effect of temperature on absorbent density.

Water concentration is 30% by weight.

PLATE B-I

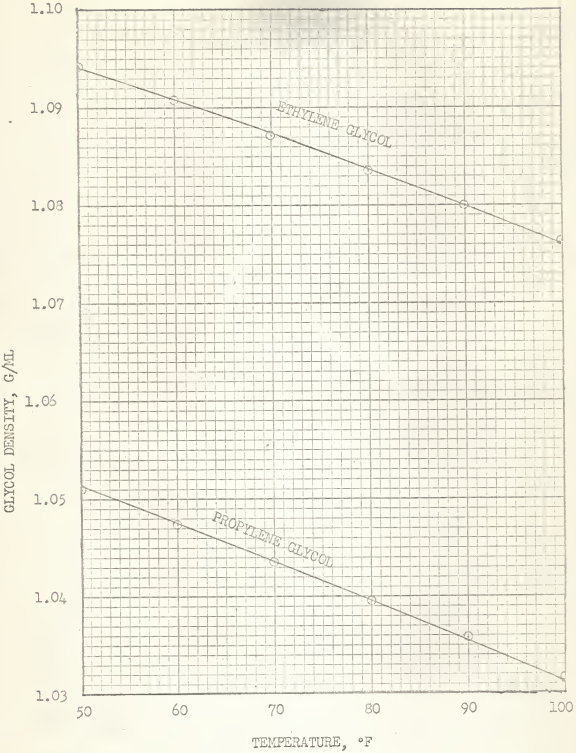

1.10
1.09
1.08
1.07
1.06
1.05
1.04
1.03
GLYCOL DENSITY, G/ML
ETHYLENE GLYCOL
PROPYLENE GLYCOL
50
60
70
80
90
100
TEMPERATURE, °F

PLATE B-II

Effect of temperature on absorbent viscosity.

Water concentration is 10% by weight.

PLATE B-II

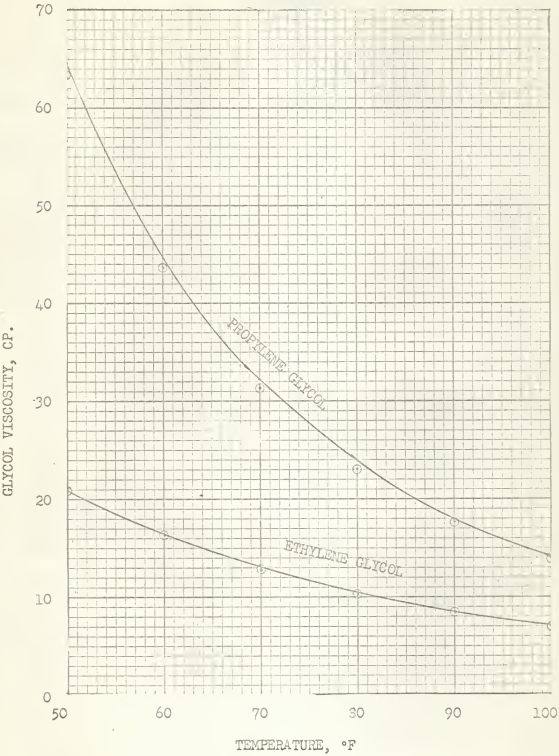

70
60
50
40
30
20
10
0
50
60
70
30
90
100
GLYCOL VISCOSITY, CP.
TEMPERATURE, °F
PROPYLENE GLYCOL
ETHYLENE GLYCOL

PLATE B-III

Effect of water concentration on surface tension.

PLATE B-III

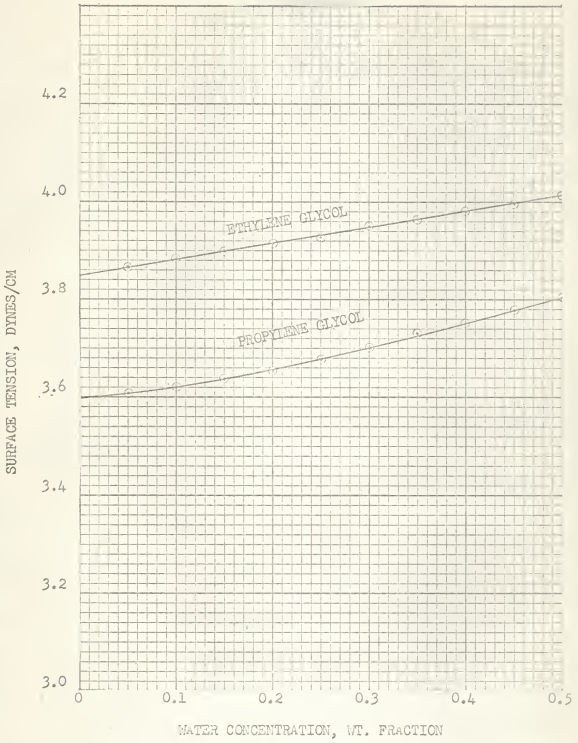

4.2
4.0
3.8
3.6
3.4
3.2
3.0
SURFACE TENSION, DYNES/CM
ETHYLENE GLYCOL
PROPYLENE GLYCOL
0
0.1
0.2
0.3
0.4
0.5
WATER CONCENTRATION, WT. FRACTION

PLATE B-IV

Effect of temperature on vapor pressure of absorbent.

Water concentration is 5% by weight.

PLATE B-IV

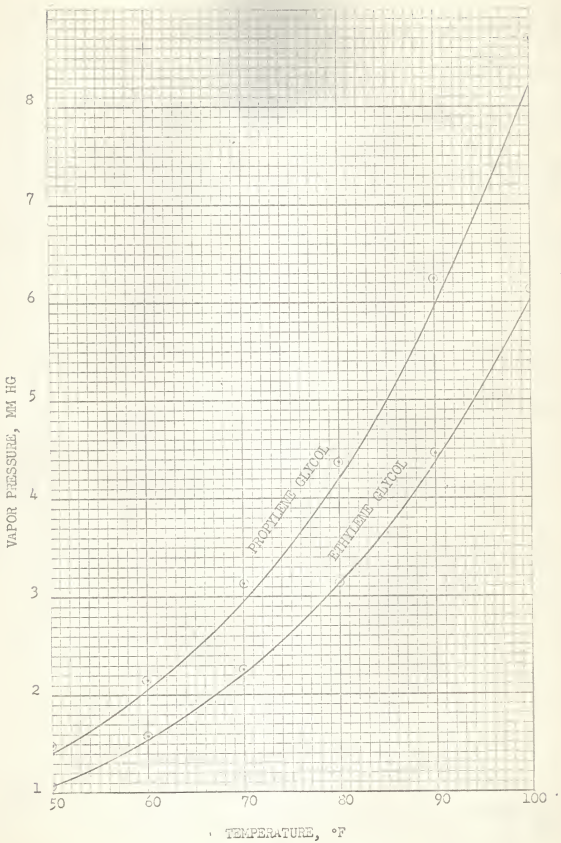
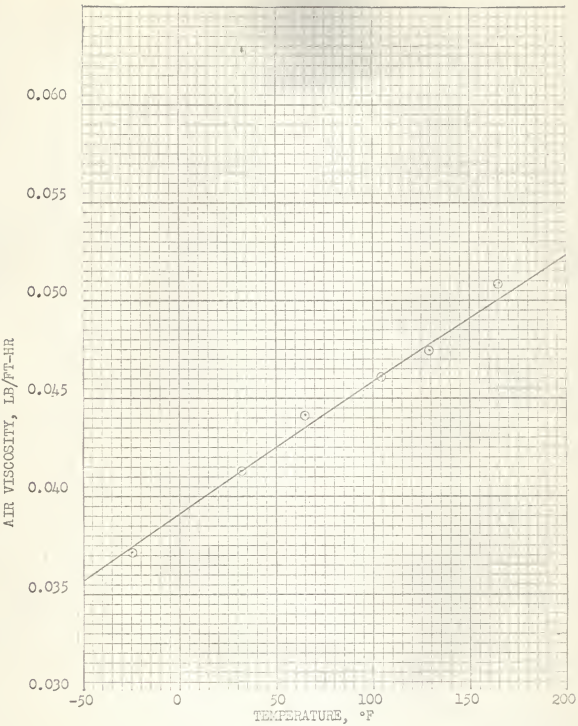

VAPOR PRESSURE, MM HG
8
7
6
5
4
3
2
1
50
60
70
80
90
100
TEMPERATURE, °F
PROPYLENE GLYCOL
ETHYLENE GLYCOL

PLATE B-V

Effect of temperature on air viscosity.

PLATE B-V


0.060
0.055
0.050
0.045
0.040
0.035
0.030
AIR VISCOSITY, LB/FT-HR
-50
0
50
100
150
200
TEMPERATURE, °F

APPENDIX C

SAMPLE CALCULATIONS

The sample calculations are based on sample 29 of the ethylene glycol data. The raw data used in the calculations are:

$w = 6$ in.

$l = 6$ in.

$u = 458.8$ ft./min.

$Q = 10.85$ cc./min.

$T = 86.4°F$

$P = 734.4$ mm. Hg

$p_A = 17.00$ mm. Hg

$x_o = 0.0306$

$x_l = 0.0986$

$x_f = 0.1053$

$t = 0.069$ in.

$t_c = 0.026$ in.

The physical properties of glycol and air were calculated with the curve fits of Appendix B. The following physical properties values were calculated.

$\rho_o = 1.1037$ g./ml.

$\rho_a = 1.0985$ g./ml.

$\mu_a = 9.1315$ centipoise

$\sigma_a = 48.5799$ dynes/cm.

$p_{eq} = 8.8458$ mm. Hg

$\mu_G = 0.04499$ lb./(hr.)(ft.)

$\rho_G = 0.07016$ lb./cu.ft.

The compositions used in calculating μ_a, ρ_a, and σ_a are the arithmetic averages of the top and bottom compositions.

1. Calculation of N_A/G_M.

$G = (1-x_o)Q_o$

$G = (1-0.0306)(10.85)(1.1037) = 11.6089$ g. glycol/min.

$W_i = x_i G/(1-x_i) = (0.0986)(11.6089)/(1-0.0986) = 1.2698$ g. water/min.

$W_f = x_f G/(1-x_f) = (0.1053)(11.6089)/(1-0.1053) = 1.3663$ g. water/min.

$\mathcal{M} = (W_f - W_i)/M_{water} = (1.3663-1.2698)/18.016 = 0.005353$ mol. water transferred/min.

$N_A = \mathcal{M}/wl = 0.005353/(15.24)(15.24) = 0.00002305$ mol./(min.)(sq.cm.)

$\Delta P = p_A - p_{eq} = 17.00-8.8458 = 8.1542$ mm. Hg

$W_a = (W_i+W_f)/2 = (1.2698\ 1.3663)/2 = 1.3181$ g. water/min.

$S = G/M_{glycol} + W_a/M_{water}$

$G/M_{glycol} = 11.6089/62.1 = 0.1869$ mol. glycol/min.

$W_a/M_{water} = 1.3181/18.016 = 0.07316$ mol. water/min.

$S = 0.1869 + 0.07316 = 0.2601$ mol./min.

$t = 0.069(2.54) = 0.1753$ cm.

$A = wt = 15.24(0.1753) = 2.6710$ sq.cm.

$G_M = S/A = 0.2601/2.6710 = 0.09738$ mol./(min.)(sq.cm.)

$N_A/G_M = 0.00002305/0.09738 = 0.0002367$

2. Calculation of Sc.

$$D_v = D_{v32}\sqrt{(T+460)/492} = 0.853\sqrt{(86.4\ 460)/492} = 0.8989 \text{ sq.ft./hr.}$$

$Sc = \mu_G/\rho_G D_v = 0.04499/(0.07016)(0.8989) = 0.7132$

3. Calculation of Z.

$$Z = \mu_L \sqrt{\rho_L g_c L \sigma_L} = 22.10\sqrt{(68.55)(4.169\text{x}10^8)(0.005667)(0.003329)} = 0.02988$$

4. Calculation of Ga.

$$Ga = \rho_L^3 L^2 g / \mu_L^2 = (68.55)^3(0.005667)^2(4.169\text{x}10^8)/(22.10)^2 = 9,092,000$$

5. Calculation of Re_G.

$$Re_G = wu/\mu_G = 0.5(27,530)(0.07016)/0.04499 = 21,470$$

6. Calculation of Re_L.

$Re_L = (g+v)t/tw/\mu_L$

$g = 60G/454 = (60)(11.61)/454 = 1.534$ lb. glycol/hr.

$v = 60W_g/454 = (60)(1.318)/454 = 0.1742$ lb. water/hr.

$tw = 0.002875$ sq.ft.

$$Re_L = (1.534+0.1742)(0.005667)/(0.002875)(22.10) = 590.1546$$

7. Calculation of t/t_c.

$$t/t_c = 0.069/0.026 = 2.654$$

8. Calculation of ρ_L/ρ_G.

$$\rho_L/\rho_G = 0.07016/(1.099)(62.4) = 0.001024$$

9. Calculation of μ_L/μ_G.

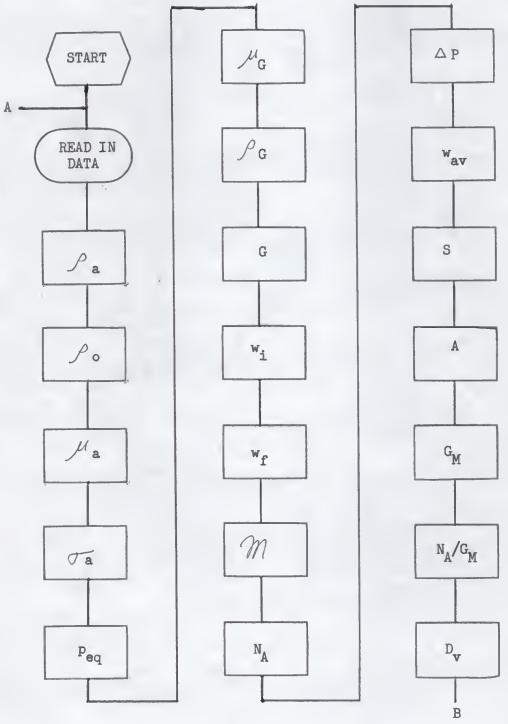
$$\mu_L/\mu_G = 0.04499/(9.131)(2.42) = 0.002036$$

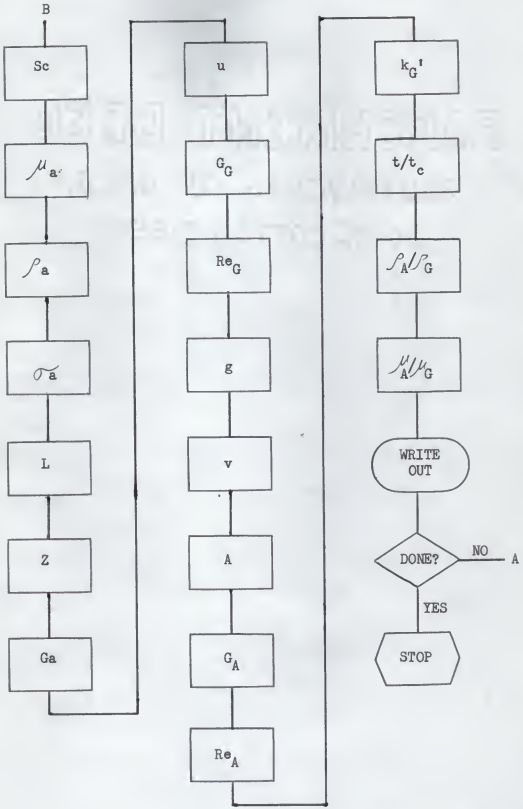
The computer language used in this program is set up so that data processing is most easily done as column vector operations. This language makes the coding of a problem of this type much simpler than would be the case for Fortran.

During checkout runs, the source program is translated into machine language by an intermediate program. Once the source program has been checked out, program cards are cut in machine language so that translation time can be avoided in future runs.

The calculations of the physical properties of the fluids was made easier by curve fitting the properties to the models given in Appendix B. The properties were then calculated from the curve fits as needed and used in the calculation of the dimensionless groups of Equation (2).

The flow sheet for the computer program is given on the following pages. The flow sheet is quite simplified in that each block may include several calculations leading to the results shown. In all cases, the calculations are identical in form to the sample calculations shown above.


START
A
READ IN DATA
ρ_a
ρ_o
μ_a
σ_a
P_{eq}
μ_G
ρ_G
G
w_i
w_f
$\mathcal{M}$
N_A
ΔP
w_{av}
S
A
G_M
N_A/G_M
D_v
B

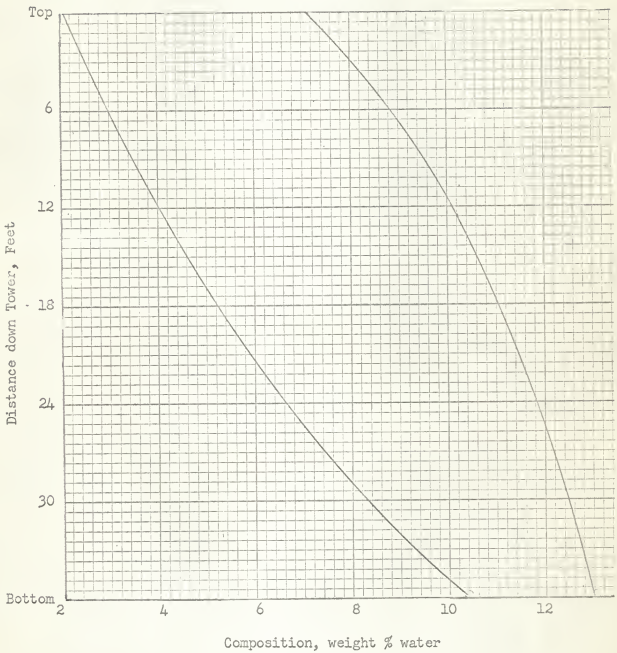

B
Sc
μ_a
ρ_a
σ_a
L
Z
Ga
u
G_G
Re_G
g
v
A
G_A
Re_A
k_G'
t/t_c
ρ_A/ρ_G
μ_A/μ_G
WRITE OUT
DONE?
NO
A
YES
STOP

APPENDIX D

COMPOSITION PROFILE

Plate D-I shows an example of each of the two types of composition profile encountered. The curve showing an increasing concentration gradient is typical of a feed having a low concentration of water. The second curve is typical of a feed with a higher concentration of water. In the second case, the absorbent stream is approaching equilibrium and the concentration gradient decreases down the column.

PLATE D-I


Top
6
12
18
24
30
Bottom
Distance down Tower, Feet
2
4
6
8
10
12
Composition, weight % water

APPENDIX E

RAW DATA

The following pages give the raw data from which the dimensionless groups were calculated by the IBM 7094 computer. The data are identified by column heading and sample number. These data were used to calculate the dimensionless groups as shown in Appendix C.

ETHYLENE GLYCOL

	w	l	u	Q	T	P
1	6.0	6.0	0.	10.850	84.20	738.00
2	6.0	6.0	0.	10.850	84.20	738.00
3	6.0	6.0	0.	10.850	84.20	738.00
4	6.0	6.0	0.	10.850	84.20	738.00
5	6.0	6.0	0.	10.850	84.20	738.00
6	6.0	6.0	0.	10.850	84.20	738.00
7	6.0	6.0	0.	10.850	82.20	737.00
8	6.0	6.0	0.	10.850	82.20	737.00
9	6.0	6.0	0.	10.850	82.20	737.00
10	6.0	6.0	0.	10.850	82.20	737.00
11	6.0	6.0	0.	10.850	82.20	737.00
12	6.0	6.0	0.	10.850	82.20	737.00
13	6.0	6.0	203.00	10.850	80.40	738.00
14	6.0	6.0	203.00	10.850	80.40	738.00
15	6.0	6.0	203.00	10.850	80.40	738.00
16	6.0	6.0	203.00	10.850	80.40	738.00
17	6.0	6.0	203.00	10.850	80.40	738.00
18	6.0	6.0	203.00	10.850	80.40	738.00
19	6.0	6.0	466.10	10.850	84.20	735.20
20	6.0	6.0	466.10	10.850	84.20	735.20
21	6.0	6.0	466.10	10.850	84.20	735.20
22	6.0	6.0	466.10	10.850	84.20	735.20
23	6.0	6.0	466.10	10.850	84.20	735.20
24	6.0	6.0	466.10	10.850	84.20	735.20
25	6.0	6.0	458.80	10.850	86.40	734.40
26	6.0	6.0	458.80	10.850	86.40	734.40
27	6.0	6.0	458.80	10.850	86.40	734.40
28	6.0	6.0	458.80	10.850	86.40	734.40
29	6.0	6.0	458.80	10.850	86.40	734.40
30	6.0	6.0	458.80	10.850	86.40	734.40
31	6.0	6.0	778.60	10.850	79.70	734.80
32	6.0	6.0	778.60	10.850	79.70	734.80
33	6.0	6.0	778.60	10.850	79.70	734.80
34	6.0	6.0	778.60	10.850	79.70	734.80
35	6.0	6.0	778.60	10.850	79.70	734.80
36	6.0	6.0	778.60	10.850	79.70	734.80
37	6.0	6.0	0.	10.850	73.40	741.30
38	6.0	6.0	0.	10.850	73.40	741.30
39	6.0	6.0	0.	10.850	73.40	741.30
40	6.0	6.0	0.	10.850	73.40	741.30
41	6.0	6.0	0.	10.850	73.40	741.30
42	6.0	6.0	0.	10.850	73.40	741.30
43	6.0	6.0	0.	10.850	77.70	740.20
44	6.0	6.0	0.	10.850	77.70	740.20
45	6.0	6.0	0.	10.850	77.70	740.20
46	6.0	6.0	0.	10.850	77.70	740.20
47	6.0	6.0	0.	10.850	77.70	740.20

	w	l	u	Q	T	P
48	6.0	6.0	0.	10.850	77.70	740.20
49	6.0	6.0	311.80	1.950	80.10	738.10
50	6.0	6.0	311.80	1.950	80.10	738.10
51	6.0	6.0	311.80	1.950	80.10	738.10
52	6.0	6.0	311.80	1.950	80.10	738.10
53	6.0	6.0	311.80	1.950	80.10	738.10
54	6.0	6.0	311.80	1.950	80.10	738.10
55	6.0	6.0	353.50	1.950	77.20	739.80
56	6.0	6.0	353.50	1.950	77.20	739.80
57	6.0	6.0	353.50	1.950	77.20	739.80
58	6.0	6.0	353.50	1.950	77.20	739.80
59	6.0	6.0	353.50	1.950	77.20	739.80
60	6.0	6.0	353.50	1.950	77.20	739.80
61	6.0	6.0	267.80	1.950	83.10	739.80
62	6.0	6.0	267.80	1.950	83.10	739.80
63	6.0	6.0	267.80	1.950	83.10	739.80
64	6.0	6.0	267.80	1.950	83.10	739.80
65	6.0	6.0	267.80	1.950	83.10	739.80
66	6.0	6.0	267.80	1.950	83.10	739.80
67	6.0	6.0	353.00	1.950	84.00	735.70
68	6.0	6.0	353.00	1.950	84.00	735.70
69	6.0	6.0	353.00	1.950	84.00	735.70
70	6.0	6.0	353.00	1.950	84.00	735.70
71	6.0	6.0	353.00	1.950	84.00	735.70
72	6.0	6.0	353.00	1.950	84.00	735.70
73	6.0	6.0	414.70	1.950	83.50	731.60
74	6.0	6.0	414.70	1.950	83.50	731.60
75	6.0	6.0	414.70	1.950	83.50	731.60
76	6.0	6.0	414.70	1.950	83.50	731.60
77	6.0	6.0	414.70	1.950	83.50	731.60
78	6.0	6.0	414.70	1.950	83.50	731.60
79	6.0	6.0	411.10	1.950	78.30	729.60
80	6.0	6.0	411.10	1.950	78.30	729.60
81	6.0	6.0	411.10	1.950	78.30	729.60
82	6.0	6.0	411.10	1.950	78.30	729.60
83	6.0	6.0	411.10	1.950	78.30	729.60
84	6.0	6.0	411.10	1.950	78.30	729.60
85	6.0	6.0	417.00	1.950	81.30	727.50
86	6.0	6.0	417.00	1.950	81.30	727.50
87	6.0	6.0	417.00	1.950	81.30	727.50
88	6.0	6.0	417.00	1.950	81.30	727.50
89	6.0	6.0	417.00	1.950	81.30	727.50
90	6.0	6.0	417.00	1.950	81.30	727.50

ETHYLENE GLYCOL

	P_A	x_o	x_i	x_f	t
1	14.13	0.0194	0.0194	0.0317	0.0680
2	14.13	0.0194	0.0317	0.0428	0.0680
3	14.13	0.0194	0.0428	0.0540	0.0680
4	14.13	0.0194	0.0540	0.0696	0.0680
5	14.13	0.0194	0.0696	0.0808	0.0680
6	14.13	0.0194	0.0808	0.1042	0.0680
7	15.48	0.0205	0.0205	0.0320	0.0680
8	15.48	0.0205	0.0320	0.0428	0.0680
9	15.48	0.0205	0.0428	0.0529	0.0680
10	15.48	0.0205	0.0529	0.0688	0.0680
11	15.48	0.0205	0.0688	0.0843	0.0680
12	15.48	0.0205	0.0843	0.0864	0.0680
13	14.69	0.1187	0.1187	0.1344	0.0740
14	14.69	0.1187	0.1344	0.1396	0.0740
15	14.69	0.1187	0.1396	0.1433	0.0740
16	14.69	0.1187	0.1433	0.1462	0.0740
17	14.69	0.1187	0.1462	0.1489	0.0740
18	14.69	0.1187	0.1489	0.1514	0.0740
19	15.89	0.1122	0.1122	0.1210	0.0690
20	15.89	0.1122	0.1210	0.1299	0.0690
21	15.89	0.1122	0.1299	0.1389	0.0690
22	15.89	0.1122	0.1389	0.1479	0.0690
23	15.89	0.1122	0.1479	0.1527	0.0690
24	15.89	0.1122	0.1527	0.1545	0.0690
25	17.00	0.0306	0.0306	0.0540	0.0690
26	17.00	0.0306	0.0540	0.0575	0.0690
27	17.00	0.0306	0.0573	0.0585	0.0690
28	17.00	0.0306	0.0585	0.0986	0.0690
29	17.00	0.0306	0.0986	0.1053	0.0690
30	17.00	0.0306	0.1053	0.1071	0.0690
31	15.84	0.1202	0.1202	0.1339	0.0700
32	15.84	0.1202	0.1339	0.1476	0.0700
33	15.84	0.1202	0.1476	0.1616	0.0700
34	15.84	0.1202	0.1616	0.1724	0.0700
35	15.84	0.1202	0.1724	0.1758	0.0700
36	15.84	0.1202	0.1758	0.1769	0.0700
37	12.42	0.2621	0.2621	0.2639	0.0700
38	12.42	0.2621	0.2639	0.2678	0.0700
39	12.42	0.2621	0.2678	0.2776	0.0700
40	12.42	0.2621	0.2776	0.2870	0.0700
41	12.42	0.2621	0.2870	0.2888	0.0700
42	12.42	0.2621	0.2888	0.2889	0.0700
43	12.70	0.1300	0.1300	0.1377	0.0700
44	12.70	0.1300	0.1377	0.1482	0.0700
45	12.70	0.1300	0.1483	0.1696	0.0700
46	12.70	0.1300	0.1696	0.2064	0.0700
47	12.70	0.1300	0.2064	0.2256	0.0700

	P_A	x_o	x_1	x_f	t
48	12.70	0.1300	0.2256	0.2380	0.0700
49	12.34	0.0610	0.0610	0.0855	0.0700
50	12.34	0.0610	0.0855	0.1125	0.0700
51	12.34	0.0610	0.1125	0.1510	0.0700
52	12.34	0.0610	0.1510	0.1740	0.0700
53	12.34	0.0610	0.1740	0.1840	0.0700
54	12.34	0.0610	0.1840	0.1910	0.0700
55	11.13	0.0475	0.0475	0.0927	0.0700
56	11.13	0.0475	0.0927	0.1320	0.0700
57	11.13	0.0475	0.1320	0.1580	0.0700
58	11.13	0.0475	0.1580	0.1720	0.0700
59	11.13	0.0475	0.1720	0.1810	0.0700
60	11.13	0.0475	0.1810	0.1870	0.0700
61	13.12	0.0725	0.0725	0.1115	0.0700
62	13.12	0.0725	0.1115	0.1522	0.0700
63	13.12	0.0725	0.1522	0.1805	0.0700
64	13.12	0.0725	0.1805	0.1930	0.0700
65	13.12	0.0725	0.1930	0.1985	0.0700
66	13.12	0.0725	0.1985	0.2023	0.0700
67	14.09	0.1459	0.1459	0.1576	0.0700
68	14.09	0.1459	0.1576	0.1763	0.0700
69	14.09	0.1459	0.1763	0.2160	0.0700
70	14.09	0.1459	0.2160	0.2285	0.0700
71	14.09	0.1459	0.2285	0.2347	0.0700
72	14.09	0.1459	0.2347	0.2378	0.0700
73	13.22	0.0770	0.0770	0.1130	0.0700
74	13.22	0.0770	0.1130	0.1451	0.0700
75	13.22	0.0770	0.1451	0.1720	0.0700
76	13.22	0.0770	0.1720	0.1900	0.0700
77	13.22	0.0770	0.1900	0.2180	0.0700
78	13.22	0.0770	0.2180	0.2250	0.0700
79	12.19	0.0955	0.0955	0.1486	0.0700
80	12.19	0.0955	0.1486	0.1675	0.0700
81	12.19	0.0955	0.1675	0.1902	0.0700
82	12.19	0.0955	0.1902	0.2220	0.0700
83	12.19	0.0955	0.2220	0.2558	0.0700
84	12.19	0.0955	0.2558	0.2658	0.0700
85	13.65	0.1316	0.1316	0.1415	0.0700
86	13.65	0.1316	0.1415	0.1556	0.0700
87	13.65	0.1316	0.1556	0.1758	0.0700
88	13.65	0.1316	0.1758	0.2109	0.0700
89	13.65	0.1316	0.2109	0.2345	0.0700
90	13.65	0.1316	0.2345	0.2436	0.0700

PROPYLENE GLYCOL

	w	l	u	Q	T	P
1	6.0	6.0	0.	0.900	84.00	734.00
2	6.0	6.0	0.	0.900	84.00	734.00
3	6.0	6.0	0.	0.900	84.00	734.00
4	6.0	6.0	0.	0.900	84.00	734.00
5	6.0	6.0	0.	0.900	84.00	734.00
6	6.0	6.0	0.	0.900	84.00	734.00
7	6.0	6.0	0.	0.900	84.20	738.00
8	6.0	6.0	0.	0.900	84.20	738.00
9	6.0	6.0	0.	0.900	84.20	738.00
10	6.0	6.0	0.	0.900	84.20	738.00
11	6.0	6.0	0.	0.900	84.20	738.00
12	6.0	6.0	0.	0.900	84.20	738.00
13	6.0	6.0	0.	0.900	77.40	737.00
14	6.0	6.0	0.	0.900	77.40	737.00
15	6.0	6.0	0.	0.900	77.40	737.00
16	6.0	6.0	0.	0.900	77.40	737.00
17	6.0	6.0	0.	0.900	77.40	737.00
18	6.0	6.0	0.	0.900	77.40	737.00
19	6.0	6.0	728.00	3.850	80.40	738.00
20	6.0	6.0	728.00	3.850	80.40	738.00
21	6.0	6.0	728.00	3.850	80.40	738.00
22	6.0	6.0	728.00	3.850	80.40	738.00
23	6.0	6.0	728.00	3.850	80.40	738.00
24	6.0	6.0	728.00	3.850	80.40	738.00
25	6.0	6.0	924.60	3.850	84.20	735.20
26	6.0	6.0	924.60	3.850	84.20	735.20
27	6.0	6.0	924.60	3.850	84.20	735.20
28	6.0	6.0	924.60	3.850	84.20	735.20
29	6.0	6.0	924.60	3.850	84.20	735.20
30	6.0	6.0	924.60	3.850	84.20	735.20
31	6.0	6.0	1245.80	3.850	86.40	734.40
32	6.0	6.0	1245.80	3.850	86.40	734.40
33	6.0	6.0	1245.80	3.850	86.40	734.40
34	6.0	6.0	1245.80	3.850	86.40	734.40
35	6.0	6.0	1245.80	3.850	86.40	734.40
36	6.0	6.0	1245.80	3.850	86.40	734.40
37	6.0	6.0	208.00	3.850	79.70	734.80
38	6.0	6.0	208.00	3.850	79.70	734.80
39	6.0	6.0	208.00	3.850	79.70	734.80
40	6.0	6.0	208.00	3.850	79.70	734.80
41	6.0	6.0	208.00	3.850	79.70	734.80
42	6.0	6.0	208.00	3.850	79.70	734.80
43	6.0	6.0	0.	3.850	73.40	741.30
44	6.0	6.0	0.	3.850	73.40	741.30
45	6.0	6.0	0.	3.850	73.40	741.30
46	6.0	6.0	0.	3.850	73.40	741.30
47	6.0	6.0	0.	3.850	73.40	741.30

	w	l	u	Q	T	P
48	6.0	6.0	0.	3.850	73.40	741.30
49	6.0	6.0	0.	3.850	77.70	740.20
50	6.0	6.0	0.	3.850	77.70	740.20
51	6.0	6.0	0.	3.850	77.70	740.20
52	6.0	6.0	0.	3.850	77.70	740.20
53	6.0	6.0	0.	3.850	77.70	740.20
54	6.0	6.0	0.	3.850	77.70	740.20
55	6.0	6.0	148.30	0.950	80.10	738.10
56	6.0	6.0	148.30	0.950	80.10	738.10
57	6.0	6.0	148.30	0.950	80.10	738.10
58	6.0	6.0	148.30	0.950	80.10	738.10
59	6.0	6.0	148.30	0.950	80.10	738.10
60	6.0	6.0	148.30	0.950	80.10	738.10
61	6.0	6.0	131.50	0.950	77.20	739.80
62	6.0	6.0	131.50	0.950	77.20	739.80
63	6.0	6.0	131.50	0.950	77.20	739.80
64	6.0	6.0	131.50	0.950	77.20	739.80
65	6.0	6.0	131.50	0.950	77.20	739.80
66	6.0	6.0	131.50	0.950	77.20	739.80
67	6.0	6.0	127.40	0.950	83.10	739.80
68	6.0	6.0	127.40	0.950	83.10	739.80
69	6.0	6.0	127.40	0.950	83.10	739.80
70	6.0	6.0	127.40	0.950	83.10	739.80
71	6.0	6.0	127.40	0.950	83.10	739.80
72	6.0	6.0	127.40	0.950	83.10	739.80
73	6.0	6.0	132.60	0.950	84.00	735.70
74	6.0	6.0	132.60	0.950	84.00	735.70
75	6.0	6.0	132.60	0.950	84.00	735.70
76	6.0	6.0	132.60	0.950	84.00	735.70
77	6.0	6.0	132.60	0.950	84.00	735.70
78	6.0	6.0	132.60	0.950	84.00	735.70
79	6.0	6.0	153.60	0.950	83.50	731.60
80	6.0	6.0	153.60	0.950	83.50	731.60
81	6.0	6.0	153.60	0.950	83.50	731.60
82	6.0	6.0	153.60	0.950	83.50	731.60
83	6.0	6.0	153.60	0.950	83.50	731.60
84	6.0	6.0	153.60	0.950	83.50	731.60
85	6.0	6.0	155.20	0.950	78.30	729.60
86	6.0	6.0	155.20	0.950	78.30	729.60
87	6.0	6.0	155.20	0.950	78.30	729.60
88	6.0	6.0	155.20	0.950	78.30	729.60
89	6.0	6.0	155.20	0.950	78.30	729.60
90	6.0	6.0	155.20	0.950	78.30	729.60
91	6.0	6.0	125.00	0.950	81.30	727.50
92	6.0	6.0	125.00	0.950	81.30	727.50
93	6.0	6.0	125.00	0.950	81.30	727.50
94	6.0	6.0	125.00	0.950	81.30	727.50
95	6.0	6.0	125.00	0.950	81.30	727.50
96	6.0	6.0	125.00	0.950	81.30	727.50

PROPYLENE GLYCOL

	p_A	x_o	x_i	x_f	t
1	15.83	0.	0.	0.0123	0.0640
2	15.83	0.	0.0123	0.0183	0.0640
3	15.83	0.	0.0183	0.0246	0.0640
4	15.83	0.	0.0246	0.0307	0.0640
5	15.83	0.	0.0307	0.0329	0.0640
6	15.83	0.	0.0329	0.0340	0.0640
7	14.13	0.0143	0.0143	0.0421	0.0640
8	14.13	0.0143	0.0421	0.0494	0.0640
9	14.13	0.0143	0.0494	0.0538	0.0640
10	14.13	0.0143	0.0538	0.0640	0.0640
11	14.13	0.0143	0.0640	0.0771	0.0640
12	14.13	0.0143	0.0771	0.0815	0.0640
13	13.34	0.0713	0.0713	0.0888	0.0640
14	13.34	0.0713	0.0888	0.0994	0.0640
15	13.34	0.0713	0.0994	0.1077	0.0640
16	13.34	0.0713	0.1077	0.1140	0.0640
17	13.34	0.0713	0.1140	0.1225	0.0640
18	13.34	0.0713	0.1225	0.1298	0.0640
19	14.69	0.1035	0.1035	0.1444	0.0740
20	14.69	0.1035	0.1444	0.1507	0.0740
21	14.69	0.1035	0.1507	0.1529	0.0740
22	14.69	0.1035	0.1529	0.1540	0.0740
23	14.69	0.1035	0.1540	0.1544	0.0740
24	14.69	0.1035	0.1544	0.1546	0.0740
25	15.89	0.0843	0.0843	0.1152	0.0700
26	15.89	0.0843	0.1152	0.1232	0.0700
27	15.89	0.0843	0.1232	0.1270	0.0700
28	15.89	0.0843	0.1270	0.1296	0.0700
29	15.89	0.0843	0.1296	0.1317	0.0700
30	15.89	0.0843	0.1317	0.1333	0.0700
31	17.00	0.0210	0.0210	0.0269	0.0700
32	17.00	0.0210	0.0269	0.0568	0.0700
33	17.00	0.0210	0.0568	0.0762	0.0700
34	17.00	0.0210	0.0762	0.0822	0.0700
35	17.00	0.0210	0.0822	0.0844	0.0700
36	17.00	0.0210	0.0844	0.0857	0.0700
37	15.84	0.1222	0.1222	0.1417	0.0700
38	15.84	0.1222	0.1417	0.1485	0.0700
39	15.84	0.1222	0.1485	0.1504	0.0700
40	15.84	0.1222	0.1504	0.1514	0.0700
41	15.84	0.1222	0.1514	0.1520	0.0700
42	15.84	0.1222	0.1520	0.1523	0.0700
43	12.42	0.2023	0.2023	0.2095	0.0700
44	12.42	0.2023	0.2095	0.2140	0.0700
45	12.42	0.2023	0.2140	0.2174	0.0700
46	12.42	0.2023	0.2174	0.2204	0.0700
47	12.42	0.2023	0.2204	0.2247	0.0700

	p_A	x_o	x_i	x_f	t
48	12.42	0.2023	0.2247	0.2306	0.0700
49	12.70	0.1224	0.1224	0.1575	0.0700
50	12.70	0.1224	0.1575	0.1692	0.0700
51	12.70	0.1224	0.1692	0.1708	0.0700
52	12.70	0.1224	0.1708	0.1780	0.0700
53	12.70	0.1224	0.1780	0.1935	0.0700
54	12.70	0.1224	0.1935	0.1970	0.0700
55	12.34	0.0830	0.0830	0.1170	0.0700
56	12.34	0.0830	0.1170	0.1475	0.0700
57	12.34	0.0830	0.1475	0.1710	0.0700
58	12.34	0.0830	0.1710	0.1820	0.0700
59	12.34	0.0830	0.1820	0.1870	0.0700
60	12.34	0.0830	0.1870	0.1882	0.0700
61	11.13	0.0742	0.0742	0.1115	0.0700
62	11.13	0.0742	0.1115	0.1445	0.0700
63	11.13	0.0742	0.1445	0.1670	0.0700
64	11.13	0.0742	0.1670	0.1770	0.0700
65	11.13	0.0742	0.1770	0.1785	0.0700
66	11.13	0.0742	0.1785	0.1882	0.0700
67	13.12	0.0760	0.0760	0.1115	0.0700
68	13.12	0.0760	0.1115	0.1340	0.0700
69	13.12	0.0760	0.1340	0.1490	0.0700
70	13.12	0.0760	0.1490	0.1600	0.0700
71	13.12	0.0760	0.1600	0.1750	0.0700
72	13.12	0.0760	0.1750	0.1790	0.0700
73	14.09	0.1700	0.1700	0.1770	0.0700
74	14.09	0.1700	0.1770	0.1810	0.0700
75	14.09	0.1700	0.1810	0.1830	0.0700
76	14.09	0.1700	0.1830	0.1840	0.0700
77	14.09	0.1700	0.1840	0.1850	0.0700
78	14.09	0.1700	0.1850	0.1860	0.0700
79	13.22	0.0991	0.0991	0.1200	0.0700
80	13.22	0.0991	0.1200	0.1370	0.0700
81	13.22	0.0991	0.1370	0.1460	0.0700
82	13.22	0.0991	0.1460	0.1520	0.0700
83	13.22	0.0991	0.1520	0.1560	0.0700
84	13.22	0.0991	0.1560	0.1580	0.0700
85	12.19	0.0742	0.0742	0.1285	0.0700
86	12.19	0.0742	0.1285	0.1417	0.0700
87	12.19	0.0742	0.1417	0.1493	0.0700
88	12.19	0.0742	0.1493	0.1550	0.0700
89	12.19	0.0742	0.1550	0.1987	0.0700
90	12.19	0.0742	0.1987	0.2086	0.0700
91	13.65	0.0845	0.0845	0.1332	0.0700
92	13.65	0.0845	0.1332	0.1448	0.0700
93	13.65	0.0845	0.1448	0.1500	0.0700
94	13.65	0.0845	0.1500	0.1590	0.0700
95	13.65	0.0845	0.1590	0.1765	0.0700
96	13.65	0.0845	0.1765	0.1882	0.0700

MASS TRANSFER FROM A VERY DILUTE GAS PHASE

by

RICHARD J. LIVINGSTON

B. S., Kansas State University, 1959

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Chemical Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1965

Two-phase mass transfer was studied in which water was absorbed from air with ethylene glycol and propylene glycol.

Equipment was designed to enable a large quantity of low concentration vapor to be brought into contact with the absorbing liquid. The contact equipment consisted of a vertical, flat plate which supported a liquid surface.

Dimensional analysis was used to provide a model with which to correlate the absorption data. The correlation was performed by the least squares method on the linearized model.

Statistical analysis of the correlated data showed that the model selected does not provide a complete explanation of the variation in the data. The coefficient of determination, R^2, which is a measure of how well the model explains variation in the data, is 37.1% for ethylene glycol and 28.4% for propylene glycol. The low values of R^2 indicates that further study should be done to provide a better model.